# Lunar Volatile Dynamics and the Lunar Ice Cube Mission

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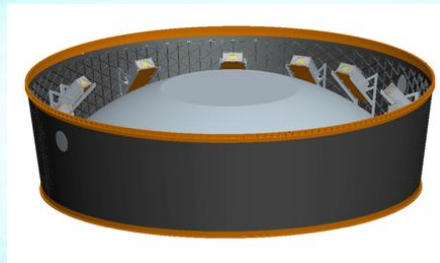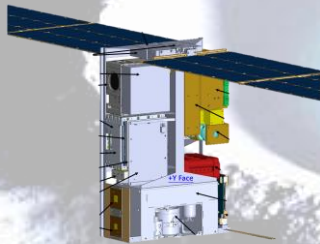
EM1 Deployment System
for the 'lucky 13'

**Jet Propulsion Laboratory**
California Institute of Technology

**National Aeronautics and Space Administration**

**Jet Propulsion Laboratory**
California Institute of Technology
Pasadena, California
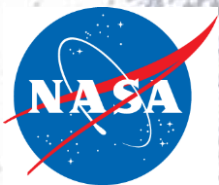
# Current Status

Launch Delay of >1 year, spacecraft delivery delay of 9 months (now end of 2018).

CDR held in June 2017.  Preparing for Delta CDR for Flight Software.

All critical / long-lead Flight hardware has been ordered.

FlatSat with non rad-hard subsystems and emulators is close to completion.

Trajectory, navigation, and thermal models along with communications links, mass, volume and power budgets evolving and achieving convergence.

Development and testing Data System beginning during this quarter.

A SPIE Optics paper on BIRCHES published. Paper on mission in progress.

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**BIRCHES and Lunarcubes: Building the First Deep Space Cubesat Broadband IR Spectrometer**

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**ABSTRACT**

The Broadband InfraRed Compact High-resolution Exploration Spectrometer (BIRCHES), which will be described in detail here, is the compact broadband IR spectrometer of the Lunar Ice Cube mission. Lunar Ice Cube is one of 13 6U cubesats that will be deployed by EM1 in cislunar space, qualifying as lunarcubes. The LunarCube paradigm is a proposed approach for extending the affordable CubeSat standard to support access to deep space via cis-lunar/lunar missions. Because the lunar environment contains analogs of most solar system environments, the Moon is an ideal target for both testing critical deep space capabilities and understanding solar system formation and processes. Effectively, as developments are occurring in parallel, 13 prototype deep space cubesats are being flown for EM1. One useful outcome of this 'experiment' will be to determine to what extent it is possible to develop a lunarcube 'bus' with standardized interfaces to all subsystems using reasonable protocols for a variety of payloads.  The lunar ice cube mission was developed as the test case in a GSFC R&D study to determine whether the cubesat paradigm could be applied to deep space, science requirements driven missions, and BIRCHES was its payload. Here, we present the design and describe the ongoing development, and testing, in the context of the challenges of using the cubesat paradigm to fly a broadband IR spectrometer in a 6U platform, including minimal funding and extensive need for leveraging existing assets and relationships on development, the foreshortened schedule for payload delivery on testing, and minimum bandwidth translating into simplified or canned operation.

**Keywords:** cubesat, broadband IR, lunarcubes, lunar orbiter, 6U, EM1

## 1. INSTRUMENT OVERVIEW

The versatile GSFC-developed payload BIRCHES (**Figure 1**), Broadband (1 to 4 micron) InfraRed Compact, High-resolution Exploration Spectrometer, is a miniaturized version of OVIRS (Osiris-Rex Visible InfraRed Spectrometer) on OSIRIS-Rex [1]. BIRCHES is a compact (1.5U, 2 kg, 12-25 W) point spectrometer with a compact cryocooled HgCdTe focal plane array for broadband measurements. The instrument includes an IRIS/AIM microcryocooler and controller [2]. The instrument will achieve sufficient SNR (>100) and spectral resolution (10 nm) through the use of a Linear Variable Filter to characterize and distinguish several spectral features associated with water in the 3-micron region, and potentially other volatiles already detected by LCROSS ($H_2S$, $NH_3$, $CO_2$, $CH_4$, OH, organics) and mineral bands. Typical footprint size will be 10 x 10 km, but will be somewhat smaller at the equator and larger toward the poles. We are also developing compact instrument electronics that can be easily reconfigured to support future instruments with Teledyne H1RG focal plane arrays [1] in 'imager' mode, when the communication downlink bandwidth becomes available.  The instrument will enable the Lunar Ice Cube (**Figure 2**) mission science goals: determination of composition and distribution of volatiles in lunar regolith as a function of time of day, latitude, regolith age and composition, and thus enable understanding of current dynamics of lunar volatile sources, sinks, and processes, with implications for evolutionary origin of volatiles.

# Lunar Ice Cube Science Goals

| Goals | Measurements | HEOMD SKG | Current Context |
|---|---|---|---|
| Primary: Determine distribution of forms and components of water as a function of time of day as an isolated variable. Provide inputs to constrain models for water origin, production, and loss<br><br>Secondary: Consider impact of latitude, slope, and slope orientation (typical illumination and temperature range), as well as composition and age (additional impact on space weaterhing) on distribution of forms and components of water to the extent possible<br><br>Tertiary: Determine distribution of other volatiles (e.g., NH3, H2S, CO2, CH4) to extent possible<br><br>Tertiary: Consider impact of solar variations if opportunities. | IR measurements in the 1 to 4 micron region associated with volatiles, especially focused on, though not limited to, the 3 micron region at </= 10 nm spectral resolution.<br><br>Utilize existing datasets from other missions (including LRO, Lunar Prospector, LCROSS, LADEE) to correlate with other parameters listed under goals. | **1-D Polar Resources 7**: Temporal Variability and Movement Dynamics of Surface-Correlated OH and H2O deposits toward PSR retention<br><br>**1-D Polar Resources 6**:  Composition, Form and  Distribution of Polar  Volatiles<br><br>**1-C Regolith 2**: Quality/quantity/distribution/form of H species and other volatiles in mare and highlands regolith (depending on the final inclination of the Lunar IceCube orbit) | More evidence for surface ice near south pole and solar exposure related effects |

## Technology Goals
## Demonstrate Enabling Technologies for Interplanetary Cubesats

- **Busek BIT 3** - High isp RF Ion Engine
- **NASA GSFC - BIRCHES** Miniaturized IR Spectrometer - characterize water and other volatiles with high spectral resolution (5 nm) and wavelength range (1 to 4 μm)
- **Space Micro C&DH-** Inexpensive Radiation-tolerant Subsystem
- **JPL Iris v. 2.1** Ranging Transceiver
- **BCT- XACT** ADCS w/ Star Tracker and Reaction Wheels
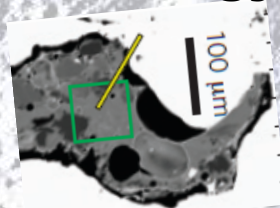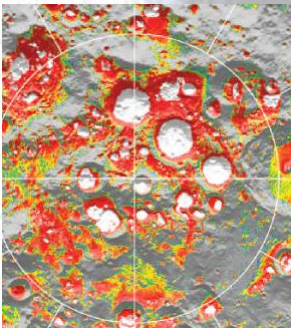- **Custom Pumpkin**- High Power (120W) CubeSat Solar Array
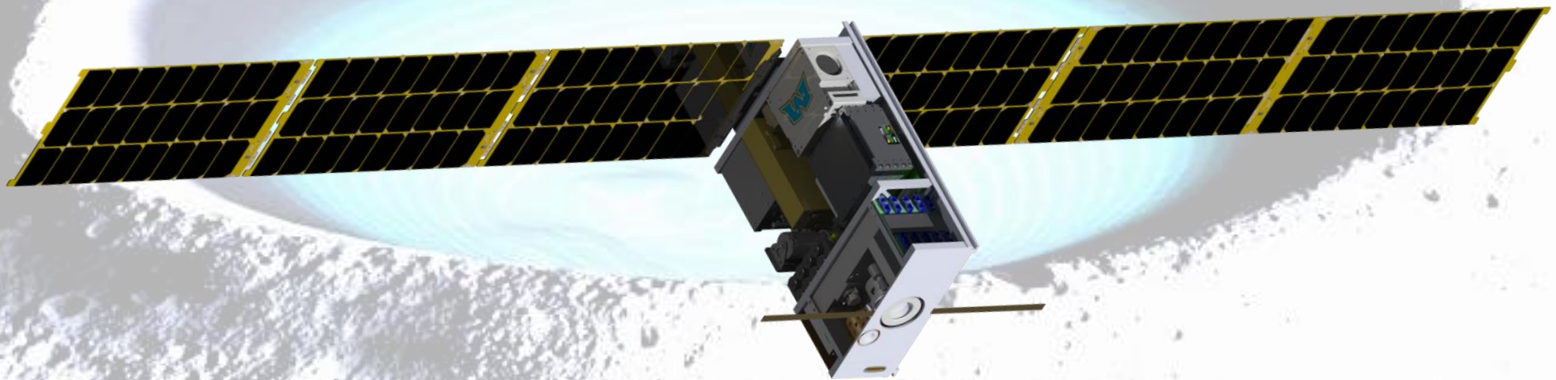
As of PDR, a de facto Science Mission as we are required to deliver science data to PDS archive.

# New View: A Lunar Water System
# Modified From Bill Farrell
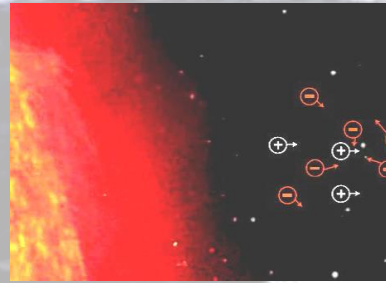
$$\partial W/\partial t + \nabla \bullet (W\mathbf{v}) = S_{SW} + S_{infall} + S_{poles}$$
$$- L_{desorp} - L_{photodiss} - L_{sputter} - L_{impactvapor}$$
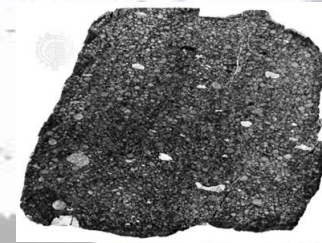
Solar
Wind (H+)

Meteoric
Infall (W, OH, V)

Hydrogen
Sub-Cycle

$H^+$

H

$H_2$ W

W, OH, V

W V V W CH OH

W V OH W OH

W V V W

V OH

V OH W

Thermal
Migration

W

W V V W V V

W OH W OH W V

Poles
(W, OH,V)

Mineralogy (OH)

W OH

Pyroclastics
(Bound H2O)

W OH OH

**Bottom Line:**

- Given BIRCHES measurements indicating variations in liquid water, ice, OH distribution across the lunar surface as function of time of day, ergo, temperature and illumination regime

- Given context of previous observations and ongoing studies

- we provide measurements that allow further examination of water, ice, and OH 'signatures' and implications for water-related processes including hydroxylation, water adsorption or desorption for:

  – Latitude and local magnetic anomalies

  – Local Slope orientation and shadowing

  – Composition, soil type, and maturity

  – Crater size and age

  – volcanic deposits

  – Transient (as opposed to systematic) effects such as impact or enhanced solar activity events

**Example of Recent Study:**
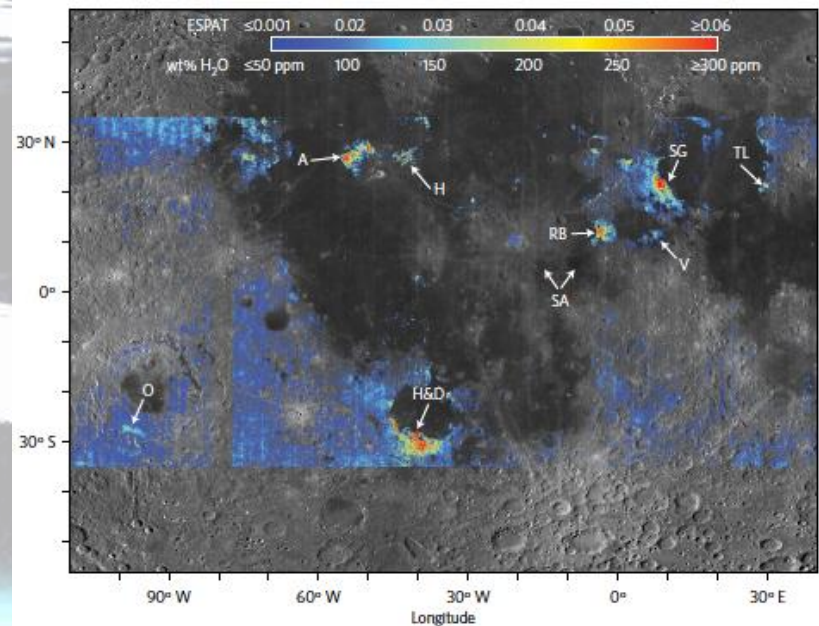


(Milliken and Li, 2017) Map of 2.85 u Effective Single Particle Absorption Thickness (ESPAT) derived from M3 at low lunar latitudes. Features apparently associated with pyroclastic deposits, lending credence to hypothesis of volatile-rich (hundreds ppm) sources in mantle. A aristarchus; O orientale, RB Rima Bode, SG Sulpicius Gallus, TL Taur-Littrow.

| Species | µm | description |
|---|---|---|
| **Water Form, Component** | | |
| water vapor | 2.738 | OH stretch |
| | 2.663 | OH stretch |
| liquid water | 3.106 | H-OH fundamental |
| | 2.903 | H-OH fundamental |
| | 1.4 | OH stretch overtone |
| | 1.9 | HOH bend overtone |
| | 2.85 | M3 Feature |
| | 2.9 | total H2O |
| hydroxyl ion | 2.7-2.8 | OH stretch  (mineral) |
| | 2.81 | OH (surface or structural) stretches |
| | 2.2-2.3 | cation-OH bend |
| | 3.6 | structural OH |
| bound H2O | 2.85 | Houck et al (Mars) |
| | 3 | H2O of hydration |
| | 2.95 | H2O stretch (Mars) |
| | 3.14 | feature w/2.95 |
| adsorbed H2O | 2.9-3.0 | R. Clark |
| ice | 1.5 | band depth-layer correlated |
| | 2 | strong feature |
| | 3.06 | Pieters et al |
| **Other Volatiles** | | |
| NH3 | 1.65, 2. 2.2 | N-H stretch |
| CO2 | 2, 2.7 | C-O vibration and overtones |
| H2S | 3 | |
| CH4/organics | 1.2, 1.7, 2.3, 3.3 | C-H stretch fundamental and overtones |
| **Mineral Bands** | | |
| pyroxene | 0.95-1 | crystal field effects, charge transfer |
| olivine | 1, 2, 2.9 | crystal field effects |
| spinels | 2 | crystal field effects |
| iron oxides | 1 | crystal field effects |
| carbonate | 2.35, 2.5 | overtone bands |
| sulfide | 3 | conduction bands |
| hydrated silicates | 3-3.5 | vibrational processes |

**anticipate wavelength of peak for water absorption band to be structural<bound<adsorbed<ice**
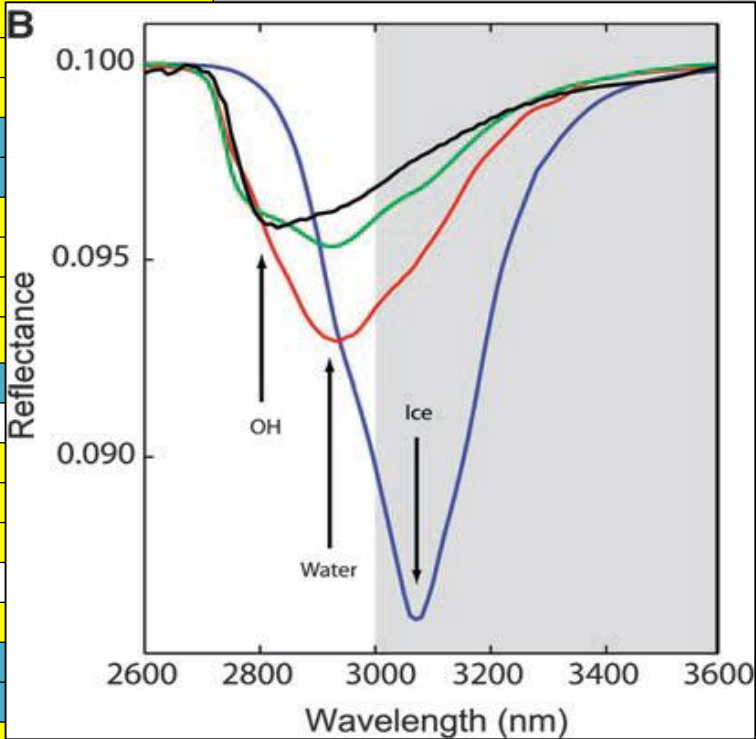


Ice Cube measurements will encompass the broad 3 um band to distinguish overlapping OH, water, and ice features. Will have near 10 nm resolution in this band

Yellow = water-related features in the 3 micron region

# Subsystems Accomplishments - BIRCHES IR SPECTROMETER
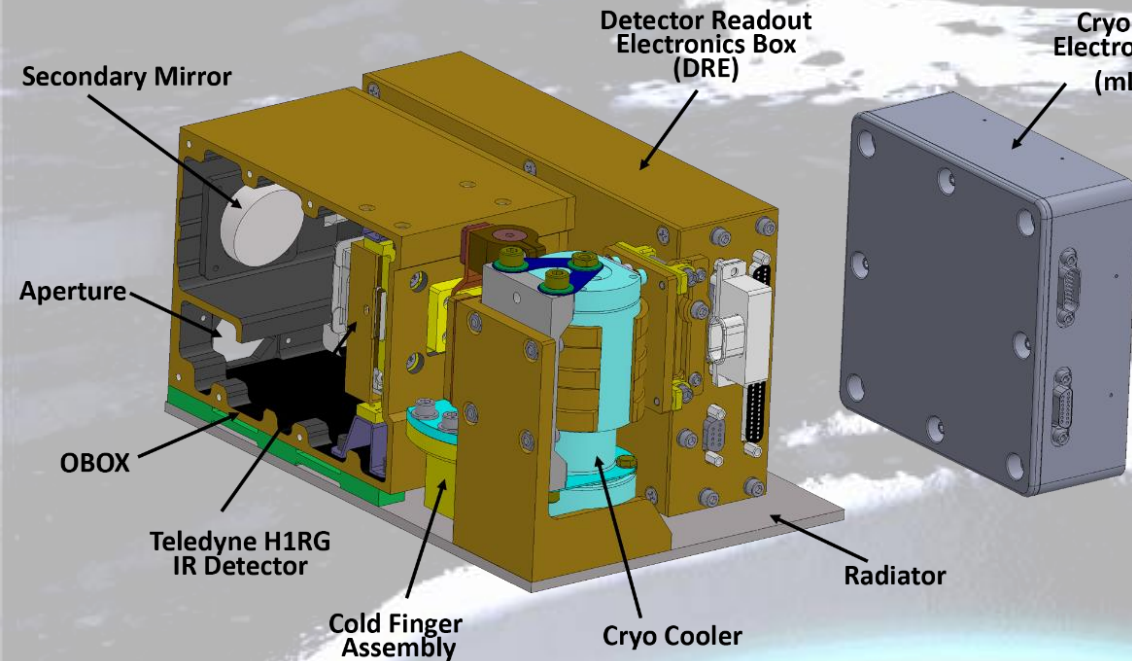


| BIRCHES compactness | | |
|---|---|---|
| Property | Ralph | BIRCHES |
| Mass kg | 11 | 3 |
| Power W | 5 | #10-20 W |
| Size cm | 49 x 40 x 29 | 10 x 10 x 15 |
| # includes 3 W detector electronics, 1.5 W AFS controller, 5-10 W cryocooler | | |

- Lightweighted Design Complete

- Specification, Interface Control Documents Complete

- Flight parts ordered or built

- ETU, Power Distribution Unit (PDU) , and Analog Processing Unit (APU) Cards Assembled

- Additional APU card being made as emulator

- Delivery date: February 2017

# Lunar Ice Cube Bus



Labels (left diagram):
- +Z Face
- Pumpkin Solar Array
- Solar Panel Pin Puller (Just Below Gimbals)
- Solar Array Gimbals
- Cryocooler Electronics Box
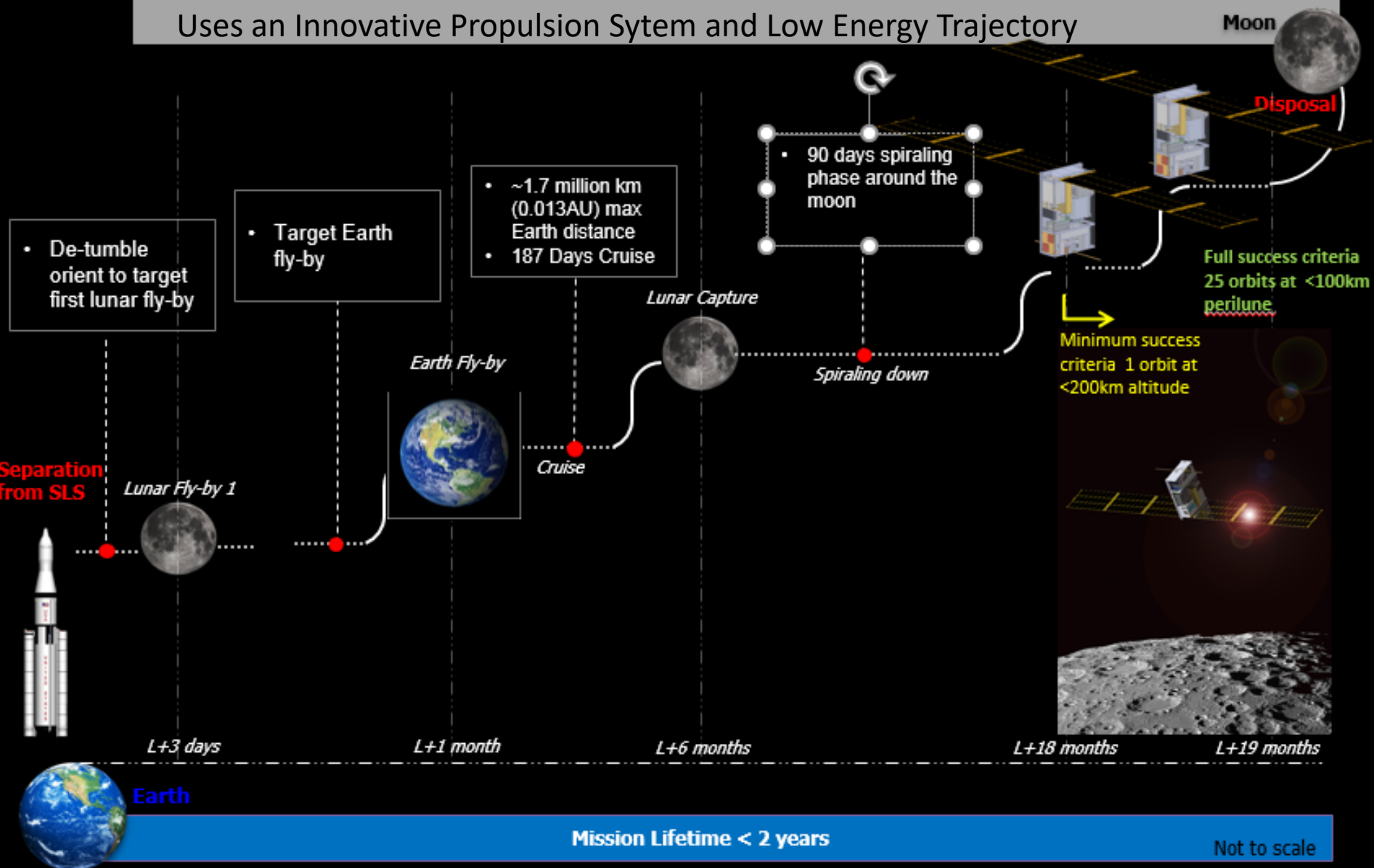- GNC: BCT XACT
- X-Band Transponder JPL Iris v.2.1
- UHF Deep Space Beacon (Under C&DH)
- +X Face
- X-Band LNA (Under C&DH)
- X-Band SSPA
- C&DH Proton 400K Lite
- X-Band Patch Antennas
- Birches IR Spectrometer
- Detector Readout Electronics Box
- Cryocooler
- +Y Face
- Battery Module
- Iodine Tank
- Pumpkin EPS
- UHF Dipole Antenna
- Busek BIT-3 Busek RF Ion Thruster

Labels (right diagram):
- Pumpkin Solar Arrays
- Cryocooler Electronics Box
- GNC: BCT XACT
- Solar Arrays Gimbals
- Proton 400K Lite (Under Transponder)
- X-Band Transponder
- Pumpkin EPS
- UHF Deep Space Beacon
- UHF Dipole Antenna
- Busek Bit-3 RF Ion Thruster
- Iodine Tank
- Battery Module
- BIRCHES IR Spectrometer
- Cryocooler
- X-Band LNA
- X-Band SSPA

# Lunar IceCube ConOps

Uses an Innovative Propulsion Sytem and Low Energy Trajectory

Moon

Disposal

- 90 days spiraling phase around the moon

Full success criteria 25 orbits at <100km perilune

Minimum success criteria 1 orbit at <200km altitude

- ~1.7 million km (0.013AU) max Earth distance
- 187 Days Cruise

- Target Earth fly-by

Lunar Capture

- De-tumble orient to target first lunar fly-by

Earth Fly-by

Spiraling down

Separation from SLS

Lunar Fly-by 1

Cruise

L+3 days

L+1 month

L+6 months

L+18 months

L+19 months

Earth

Mission Lifetime < 2 years

Not to scale

# L-IC Science Orbit



**Operations in Typical Lunar Orbit**
**~7 hours**

CDH Sends IRIS Position Sequence and START Command (Step 0). Assumes Cal and science are the same operation.

**Calibration Data**
**~2 minutes**

Comunications and/or Tracking and Ranging Mode

**Science Operations**
**~ 40 minutes**

Earth

**Calibration Data**
**~2 minutes**

CDH Sends STOP Command (Step 26)

CDH Sends Comand:Tx Data, TLM, Uplink Commands or Track/Ranging

# BIRCHES Observational Requirements

**Adjustable Field Stop can adjust the FOV from 6 to 0.6 degrees to maintain footprint at 10 km for anticipated altitudes ranging from 10 to 1000 km.**

**Nominal Footprint 10 km in along track direction regardless of altitude, consecutive observations with overlapping coverage separated by a couple of kilometers (> Nyquist Sampling)**

**Nominal Footprint 10 km in cross track direction, with overlap of consecutive tracks at poles, separted by a couple of kilometers**
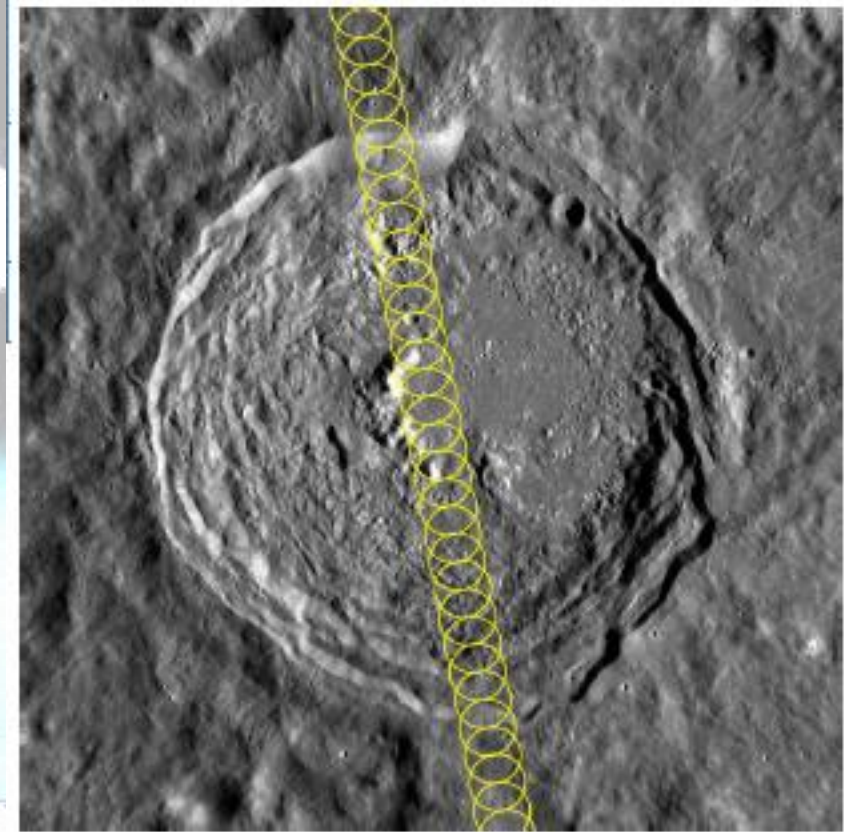


Vavilov Crater:
100 km in diameter
1° S, 138° W

**Lessons Learned**

Thermal:  A problem for 6U space cubesats with spectrometers. Possibly mitigated by advances in thermal design for next generation cubesats or by use of 12U.

BIRCHES: Still evolving strategy for stationkeeping, which requires reorienting spacecraft and turning on propulsion system, thus heating spacecraft. Optics box temperature control marginal. Mass expended to solve thermal problems (mostly) means we now have no margin.

COTS and Spares: Business as usual for cubesat 'maker' culture needs to be reinterpreted  for a deep space mission with end user requirements (aerospace science and engineering culture). Make sure what you need exists and get that in writing.

BIRCHES: The reluctance to disclose internal workings of several COTS systems, as trade secrets, has created additional challenges.  This should have been negotiated, with NDAs, at the beginning.  Some of OVIRS spares have just been found.

Flight Software: Cubesats depend on it (adaptable, reconfigurable systems to minimize resources) even more than conventional spacecraft, and yet it is never adequately prioritized and budgeted.

BIRCHES: Budget now supplemented for GSFC Core Flight Executive operating system which has many of the drivers we need thanks to its low key use in many small missions.

**Lessons Learned**

Mission Operations: Cubesat operations can be demanding, but due to lack of budget, haven't typically funded a mission operations lead. Make sure you have one.

BIRCHES: the most operationally complex and challenging cubesat mission to date has finally received some additional support to rectify this situation.

Data Management: NASA is attempting to generate shared tools for the first group of deep space cubesats, but being tied in to an existing science data center is a must. PDS Science nodes have received some subsidies but not SPICE/NAIF.

BIRCHES: We were a tech demo, now we are required to deliver science data. We are still attempting to get additional support to deliver useful science data products to the PDS Geoscience node. We will need to leverage community support to deliver higher level data products.

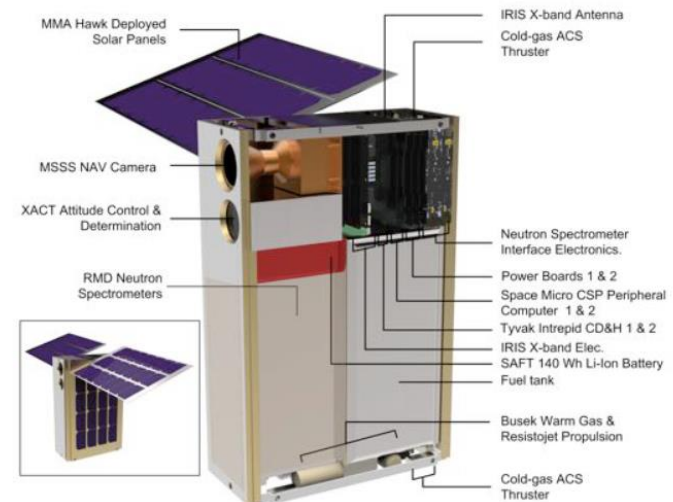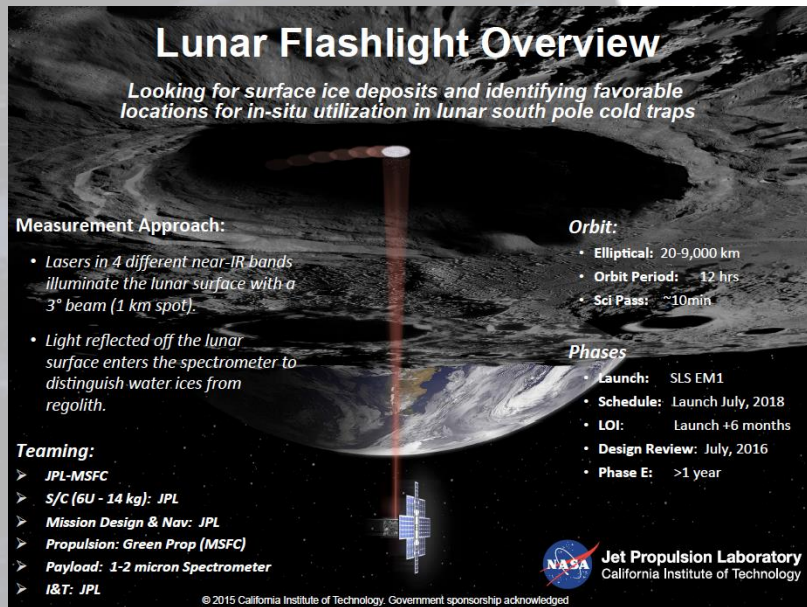# Other EM1 Mission Complimentarity





**Figure 1:** LunaH-Map cut-away showing spacecraft components and configuration. Inset image shows LunaH-Map deployed configuration.

Lunar Flashlight:  Detect surface ice for PSRs polar region by measuring laser stimulated emission at several ice-associated lines.

LunaH Map: Detect ice in top layer (tens of centimeters) of regolith for PSRs polar region by measuring decrease in neutron flux (anti-correlated with protons) using neutron spectrometer.

Lunar IceCube: Determine water forms and components abundances as a function of time of day, latitude, and lunar regolith properties using broadband point spectrometer.

# Conclusions

- BIRCHES will measure variations in liquid water, ice, OH distribution across the lunar surface as function of time of day (temperature and illumination) as well as providing basis for constraints for existing global/local volatile production/interaction models

- Lunar Ice Cube utilizes MSU cubesat bus with Busek propulsion and commercial subsystems modified for deep space, GSFC instrument and flight dynamics expertise with low energy manifolds to lunar capture, and JPL science PI and deep space communication expertise

- EM1 deployed Lunar Ice Cube lunar orbiter will deliver high priority measurements on lunar volatiles via a HEOMD NextSTEP mission selected to demonstrate technology for propulsion and compact volatile-detecting instrument capability

- Lunar Ice Cube, and the other EM1 cubesat missions measuring lunar volatiles, acting as a multi-platform cluster, are pioneering the use of the cubesat paradigm for deep space exploration.

- We are doing what cubesats are supposed to do: creating a tailored solution with a standard platform.
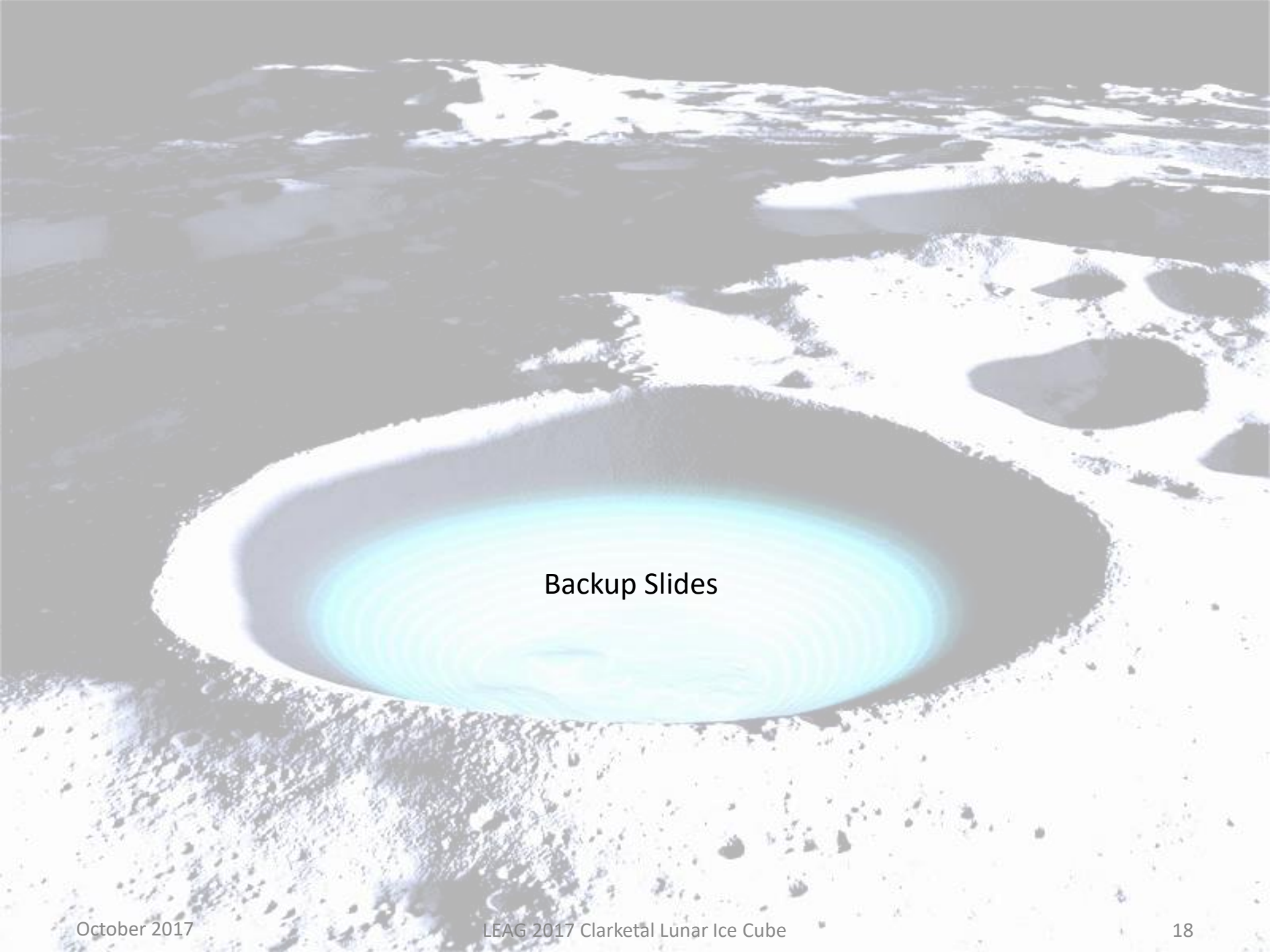
# LunarCubes Are Back!!!!
**CDW San Luis Obispo in April 2018**
**Your challenging science mission requirements needed**

**pamela.e.clark@jpl.nasa.gov**

Backup Slides

## Lunar IceCube versus Previous Missions

| Mission | Finding | IceCube |
|---|---|---|
| Cassini VIMS, Deep Impact | surface water detection, absorption vs tiime of day implying variable hydration | water & other volatiles, fully characterize 3 μm region as function of several times of day for same swaths over range of latitudes w/ context of regolith mineralogy and maturity, radiation and particle exposure, for correlation w/ previous data |
| Chandrayaan M3 | H2O and OH (<3 microns) veneer in mineralogical context  nearside snapshot at one lunation | |
| LCROSS | ice, other volatile presence and profile from impact in polar crater (greater depth) | |
| LP, LRO, LEND LAMP DVNR LOLA LROC, LADEE | H+ in first meter (LP, LEND) & at surface (LAMP) inferred as ice (cold trap) abundance via correlation with temperature (DIVINER), PSR and PFS (LROC, LOLA), H exosphere (LADEE) | |
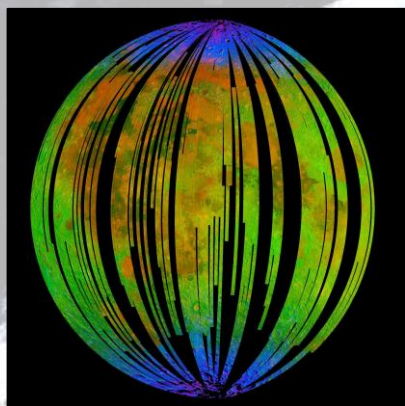


M3 'snapshot' lunar nearside indicating surface coating OH/$H_2O$ (blue) near poles (Pieters et al, 2009)

Table B.2 IR measured volatile abundance in LCROSS plume (Colaprete et al, 2010)

| Compound | Molecules $cm^{-2}$ | Relative to $H_2O(g)$* |
|---|---|---|
| H2O | 5.1(1.4)E19 | 100% |
| H2S | 8.5(0.9)E18 | 16.75% |
| NH3 | 3.1(1.5)E18 | 6.03% |
| SO2 | 1.6(0.4)E18 | 3.19% |
| C2H2 | 1.6(1.7)E18 | 3.12% |
| CO2 | 1.1(1.0)E18 | 2.17% |
| CH2OH | 7.8(4.2)E17 | 1.55% |
| CH4 | 3.3(3.0)E17 | 0.65% |
| OH | 1.7(0.4)E16 | 0.03% |

*Abundance as described in text for fit in Fig 3C
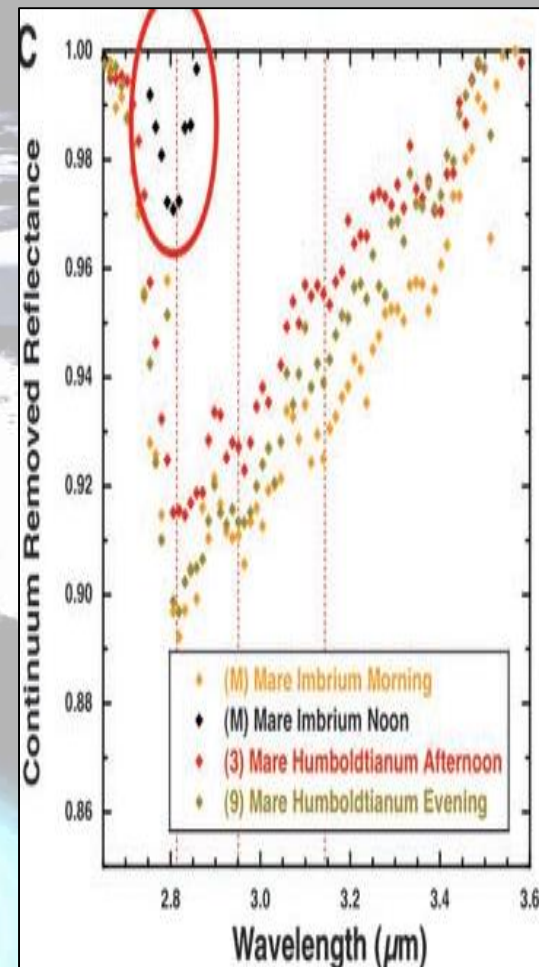


Early evidence for diurnal variation trend in OH absorption by Deep Impact (Sunshine et al. 2009) which will be geospatially linked by Lunar IceCube.
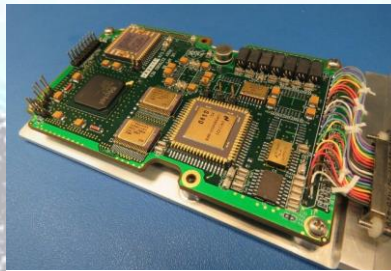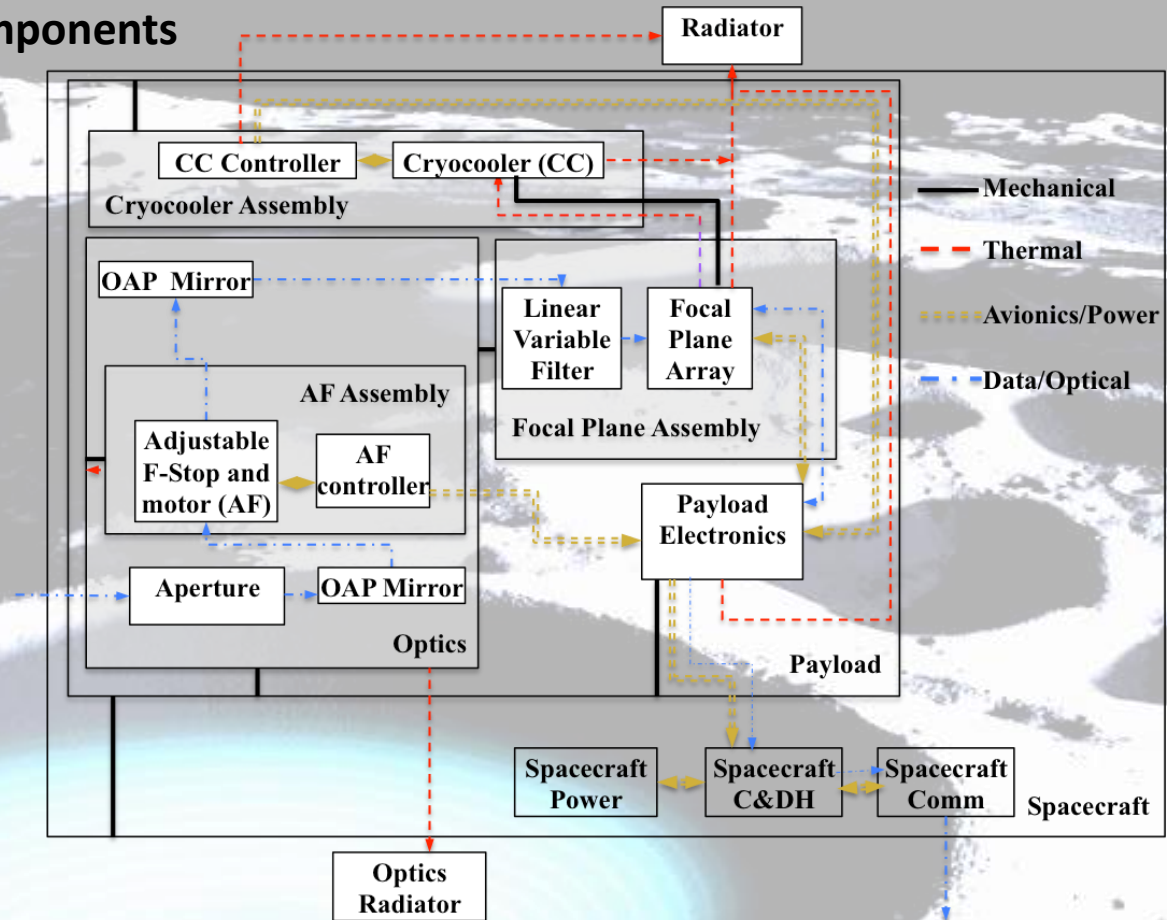
# Spectrometer Schematic and Components
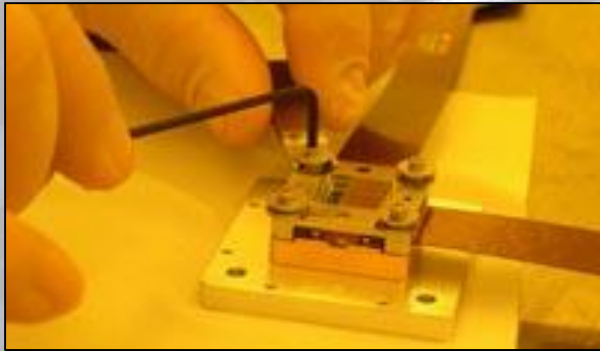


BIRCHES utilizes a compact Teledyne H1RG HgCdTe Focal Plane Array and JDSU linear variable filter leveraging OSIRIS REx OVIRS.
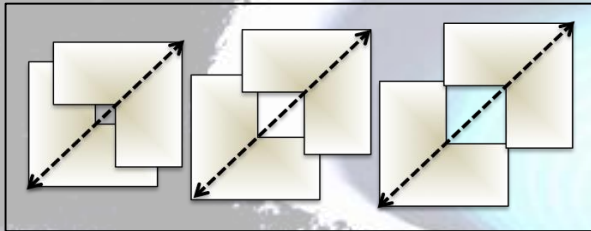


Adjustable Iris maintains footprint size at 10 km by varying FOV regardless of altitude



**Radiator**

**Cryocooler Assembly**
- CC Controller
- Cryocooler (CC)

Legend:
- ——— Mechanical
- – – – Thermal
- ·········· Avionics/Power
- – · – Data/Optical

**Optics**
- OAP Mirror
- AF Assembly
  - Adjustable F-Stop and motor (AF)
  - AF controller
- Aperture
- OAP Mirror

**Focal Plane Assembly**
- Linear Variable Filter
- Focal Plane Array

**Payload**
- Payload Electronics

**Spacecraft**
- Spacecraft Power
- Spacecraft C&DH
- Spacecraft Comm

**Optics Radiator**



BIRCHES Analog Processing Unit (APU) (top)

COTS AFRL developed AIM SX030 microcryocooler with cold finger to maintain detector at ≤115K and iris controller

# Bus Components

**Thermal Design:** with minimal radiator for interior the small form factor for BIRCHES means that interior experiences temperatures well within 0 to 40oC. Optics box which has a separate radiator to keep it below 220K. Initial thermal modeling funded via GSFC IRAD work.
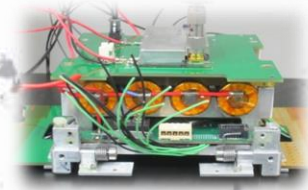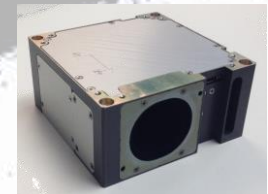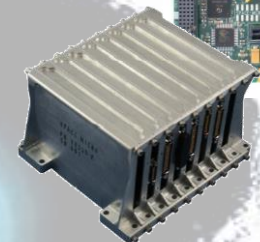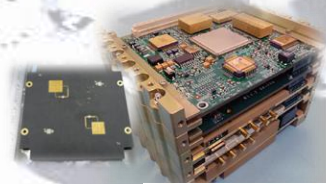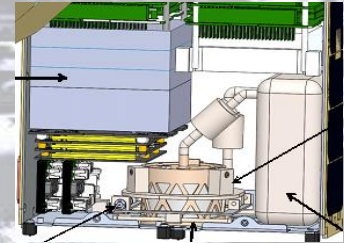
**Propulsion:** 2U Busek Gimbaled Iodine Ion Propulsion Drive (EP) with external e-source to offset charge build up. Models indicate no contamination problem.

**Communication, Tracking**: X-band, JPL Iris Radio, dual X-band patch antennas. MSU has 21-m dish that is becoming part of the DSN. Anticipated data rate 128 kb/s
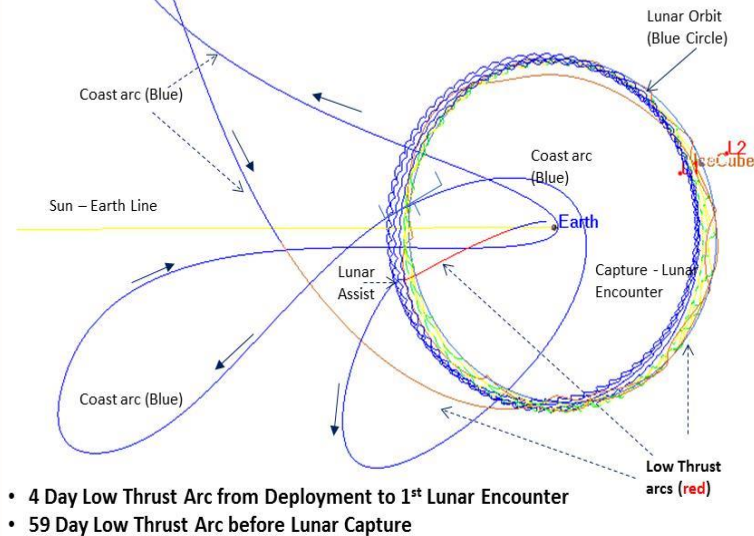
**C&DH**: Space Micro Proton 400K.

**GNC/ACS**: Modified Blue Canyon modified XACT. Multi-component (star trackers, IMU, RWA) packages. Stated Spacecraft pointing accuracy ±0.007 deg(1-sigma)
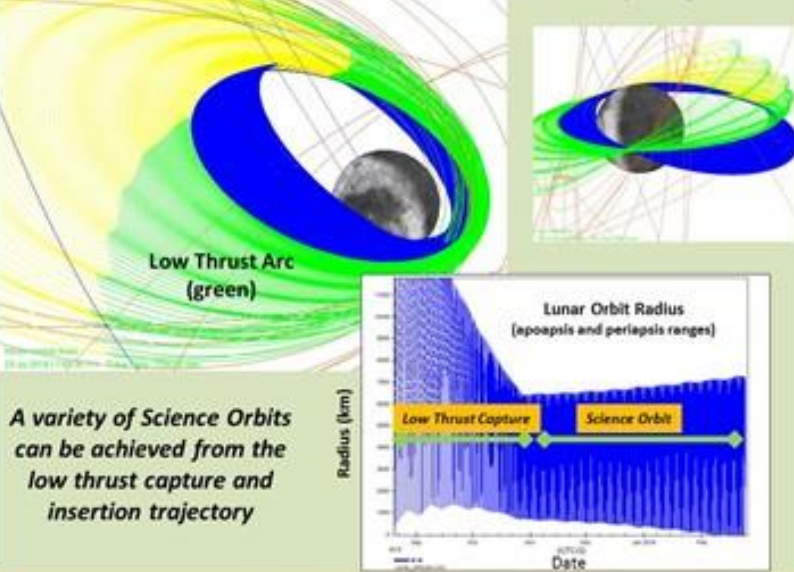
**Power System**: Pumpkin Custom Power System (Panels, Gimbals, EPS)

## Transfer Trajectory with Low Thrust
(Sun-Earth Rotating Coordinate Frame)

- 4 Day Low Thrust Arc from Deployment to 1st Lunar Encounter
- 59 Day Low Thrust Arc before Lunar Capture


Low Thrust Insertion and Science Orbit (blue)

A variety of Science Orbits can be achieved from the low thrust capture and insertion trajectory

## LWaDi 6 Month Mission Concept



dusk
LOI + 6 months

Revisit same representative (in latitude, composition, structure) features at different times of day during 6 lunar cycles

Sun

noon

LOI + 3 months

To keep perilune in Sunlight beyond 6 months, we would need to maneuver to rotate the line of apsides

dawn

Lunar Orbit Insertion (LOI)

If we choose the initial line of apsides to be orthogonal to the Sun line, we can keep perilune in Sunlight for 6 months.

Total Signal in Photons Per Second with Cos(Phase) Factor vs Wavelength in Microns

Reflectivity Part of Total Signal in Photons Per Second vs Wavelength in Microns

| Case | Lat | ToD | Temp K | Reflectivity @ 3um photons/sec | Total Signal | SNR | Band depth/PPM water | | |
|------|-----|-----|--------|-------------------------------|--------------|-----|----------|----------|----------|
| | | | | | | | 0.1/1000 | 0.05/500 | 0.01/100 |
| 1 | 0 | 87 | 163 | 3254 | 2760 | 52 | 276 | 138 | 27 |
| 2 | 60 | 0 | 335 | 39045 | 26400 | 162 | 2640 | 1320 | 264 |
| 3 | 20 | 65 | 304 | 24279 | 20963 | 145 | 2096 | 1480 | 210 |
| 4 | 0 | 0 | 395 | 150777 | 52800 | 230 | 5280 | 2640 | 528 |

**More recent studies and Bottom Line:**

- Given BIRCHES measurements indicating variations in liquid water, ice, OH distribution across the lunar surface as function of time of day, ergo, temperature and illumination regime

- Given context of previous observations and ongoing studies

- we can examine water, ice, and OH 'signatures' and implications for water-related processes including hydroxylation, water adsorption or desorption for:

  – Latitude and local magnetic anomalies

  – Local Slope orientation and shadowing

  – Composition, soil type, and maturity

  – Crater size and age

  – Transient (as opposed to systematic) effects such as impact or enhanced solar activity events



Fig. 5. Average 1064 nm reflectance as a function of maximum temperature (maximum temperature bin width = 3 K) for low slope (slope < 10°) areas free of mass wasting influence for areas within 5° of each pole, and between 5 and 20° from each pole, illustrating spatial heterogeneity in polar reflectance-temperature relationships. a) North polar data; b) South polar data. Curves plotted with 2σ standard error of the mean. Volatility thresholds for elemental sulfur and water ice are included for comparison. Thresholds were derived by Zhang and Paige (2009) a sublimation rate of 1 mm/Gyr.

Evidence for surface ice at South Pole from LRO LA (Fisher et al 2017) and for magnetic anomaly and latitudinal impacts on space weather 'darkening' (Hemingway at el 2015)
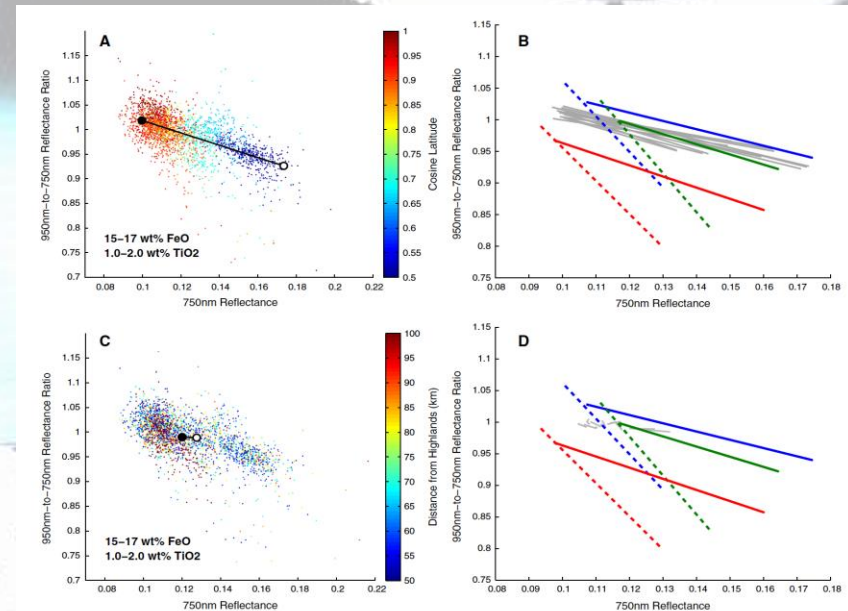


Fig. 15. Color variation of mare surfaces that are at least 50 km from the nearest highlands (compare with Fig. 4, which characterizes the entire lunar surface, and Fig. 10, which characterizes all of the maria). (A) Spectral characteristics of pixels sampled from regions with between 15 and 17 wt% FeO and between 1 and 2 wt% TiO₂. Points are color-coded according to cosine latitude, as in Fig. 4. (B) Compilation of latitudinal trends across the 13 compositional bins compared to the swirl- and impact-related trends (red, green, and blue lines). (C) Spectral characteristics of the same pixels as in (A), except that points are color-coded according to distance from the highlands: blue points correspond to locations that are 50 km from the mare/highland boundary whereas red points correspond to locations that are 100 km or more from the nearest highlands (pixels within 50 km of the nearest highlands are excluded). The black trend line represents a least squares best fit through the data points with the end points indicating the color predicted by the best-fit line at locations 50 km (white circle) and 100 km (black circle) from the mare/highland boundary. (D) Compilation of the 13 highland-distance trend lines (gray lines) compared to the swirl- and impact-related trends (red, green, and blue lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)